The Reappearance of Anomalous Cosmic Ray Hydrogen

E.R. Christian[1], A.C. Cummings[2], E.C. Stone[2]
[1]USRA Research Scientist, NASA/GSFC Code 661, Greenbelt MD 20771 USA
[2]California Institute of Technology, Pasadena, CA 91125 USA

Abstract

New observations from the Cosmic Ray Subsystem (CRS) on the Voyager spacecraft clearly show that anomalous cosmic ray hydrogen has reappeared, clearing up a controversy that has existed since the previous solar minimum [1, 2]. The new observations are consistent with the evidence for anomalous cosmic ray hydrogen seen in the 1987 solar minimum. Comparison of the anomalous and galactic cosmic ray modulation for the two solar minima indicates that there is substantial modulation of the galactic cosmic rays beyond the solar wind termination shock.

1 Introduction

It is thought that anomalous cosmic rays (ACRs) originate as interstellar neutrals that drift into the heliosphere, are either photo-ionized, or ionized by charge exchange with solar wind particles, and then are convected out to the solar wind termination shock, where they are accelerated [3, 4]. The presence of some ACR hydrogen is expected [5], and indeed, hydrogen "pick-up" ions have been seen in the solar wind [6], but until now, the evidence for ACR hydrogen has been circumstantial [1, 7]. Observations of ACR hydrogen are difficult because, whereas the other ACR components have a higher rigidity than galactic cosmic rays (GCR) at the same energy, because they are singly-ionized as opposed to the fully-ionized GCR, this is not true for ACR hydrogen. Therefore, the ACR and GCR protons undergo very similar modulation inside the termination shock.

With each successive period of minimum solar modulation, the Voyager spacecraft move closer to the termination shock and the source of anomalous cosmic rays. Voyager 1, at about 57 AU radial distance and 247° heliospheric longitude, λ, 32° latitude, β, during 94, has observed anomalous cosmic ray fluxes which are higher than those observed at Voyager 2 (~43 AU, $\lambda = 284°$, $\beta = -11°$ in 1994) or either Voyager during the 1987 solar minimum. Both Voyagers are moving roughly upstream relative to the inflowing interstellar neutrals, which are coming from $\lambda = 255°$, $\beta = -8°$ [8].

2 Observations

Figure 1 shows the spectral evolution of the proton spectra at Voyager 1 and 2 between the beginning of 1993 and the end of 1994. Because the analysis uses events from several different telescopes and trigger conditions, and there is a question of the normalization of the fluxes between these different event types, a 10% systematic error has been added in quadrature with the statistical fluctuations for points with energies <150 MeV. The >150 MeV points are from events which fully penetrate the High Energy Telescopes (HETs), and have had 15% systematic errors added because of differences in absolute flux obtained by two different analyses [9]. This makes negligible quantitative difference in the subsequent discussion.

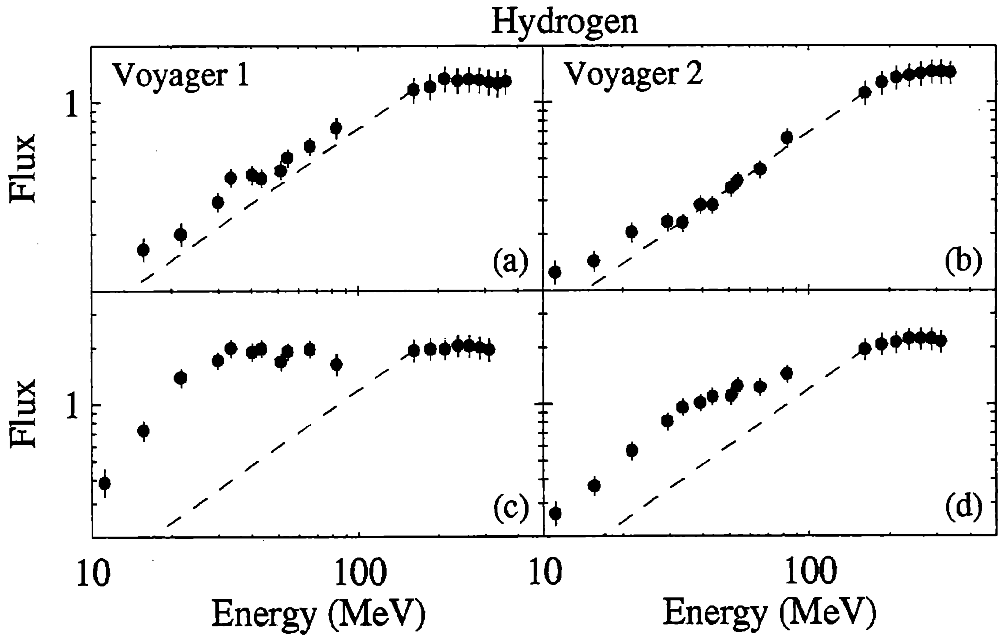

Figure 1. Observed proton energy spectra for Voyager 1 (left column) and Voyager 2 (right column) for the time periods 1993 days 53-157 (a and b) and 1994 days 313-365 (c and d). The flux is measured in particles / (m^2 sr sec MeV). The dashed lines illustrate T^{+1} slopes for the four spectra normalized to the observed flux at 162.5 MeV.

In the 1993 time period, both Voyagers appear to be dominated by a modulated galactic cosmic ray spectrum and exhibit the flux-proportional-to-kinetic-energy slope at low energies (as shown by the dashed lines) that is expected from simple modulation theory [10]. In late 1994 the story is very different, and Voyager 1 is clearly showing the double peaked spectrum characteristic of the presence of both anomalous and galactic cosmic rays, and Voyager 2 is also showing an excess in the lower energies.

3 Discussion

In order to derive the amount of ACR hydrogen, the observed Voyager 1, 1994 days 313-365 proton spectrum will be deconvolved into galactic and anomalous hydrogen. For a galactic spectrum, the shape of the Voyager 2, 1993 days 53-157 time periods will be used, because the contribution of an anomalous component should be small. Because the shape of the anomalous spectrum is evolving much more quickly than the galactic spectrum, the shape of the ACR helium for Voyager 1, 1994 days 313-365 will be used. This is derived from the observed spectrum by taking a flux-proportional-to-kinetic-energy spectrum normalized at energies greater than 100 MeV/nucleon (galactic) and subtracting that from the fluxes for energies less than 100 MeV/nucleon. A least-squares fit between a sum of these ACR and GCR spectral shapes and the observed H spectrum is then performed. This is the same method used in [7].

Figure 2 shows this deconvolution for both the Voyager 2, 1987 solar minimum data previously published in [7] and the Voyager 1, 1994 data shown in Figure 1c. The separation of the ACR and GCR components is made easier than it was in 1987 because the peak flux of ACR hydrogen is about 40 MeV for this time period, considerably lower than the ~134 MeV peak energy seen in 1987. This is expected since all of the anomalous components are at a decreased level of solar modulation in 1994, as compared to 1987. Notice that the GCR components are at similar modulation levels for the two time periods. This proportionately large change in the ACR modulation level without an equivalent change in the galactic modulation level can be explained if there is significant modulation of the galactic spectrum outside of the termination shock, as has been postulated (see e.g. [11]). Indeed, comparing the observed GCR proton spectrum to the presumed interstellar galactic proton spectrum (see e.g. [12]) shows that we are well within the modulation boundary for galactic cosmic rays, whereas we are rapidly approaching the boundary for ACRs, presumably the termination shock.

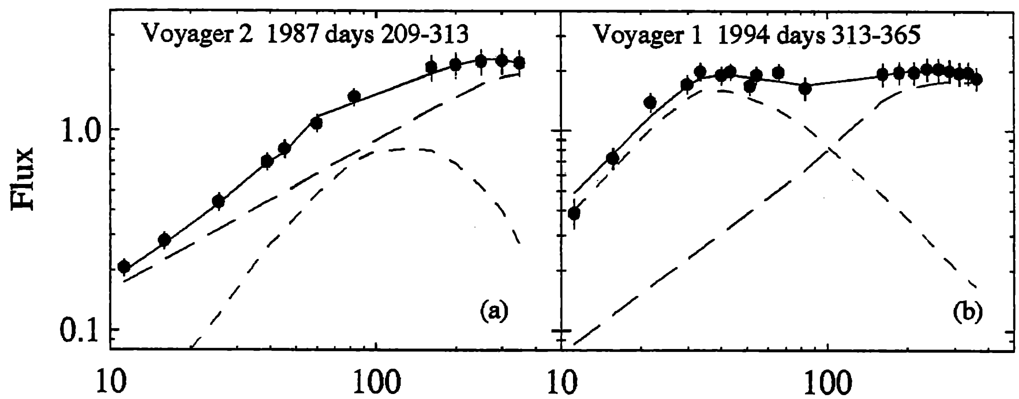

Figure 2. Decomposition of the observed proton energy spectra into anomalous cosmic ray and galactic cosmic ray components for Voyager 2 in 1987 days 209-313 (a) and Voyager 1 in 1994 days 313-365 (b). The small-dash lines show the best-fit anomalous spectra, the large-dash lines are the galactic spectra, and the solid lines are the sum, which should be compared with the observed points. The flux is in units of particles/(m^2 sr sec MeV).

The ACR H/He ratio obtained from the fit in Figure 2b is 0.41 +- 0.04, which is consistent with the 0.37 +- 0.10 obtained from Figure 2a [13], and also with the 0.37+- 0.03 obtained from an earlier 1994 time period [14].

As one step in deriving the abundances of interstellar neutrals, a more detailed comparison of the peak energy of the ACR hydrogen and other ACR components has been done [15] for these proceedings. As is shown in [15, 16, 17], the spectra of the ACR components scale as a power law in mass. In Figure 3 we show the energy divisor needed to scale the hydrogen, carbon, nitrogen, oxygen ACR components to helium. This parallels one of the pieces of evidence for ACR hydrogen presented for the 1987 solar minimum [7]. There is some difficulty in 1994 because the peak energy of the ACR components heavier than helium fall below the minimum energy observable with the Voyager CRS instruments. With this caveat though, it is clear in Figure 3 that the observed energy scaling factor all the ACR species, including hydrogen, are consistent with a power law in mass. This power is nearly identical to the one observed in 1987 [16].

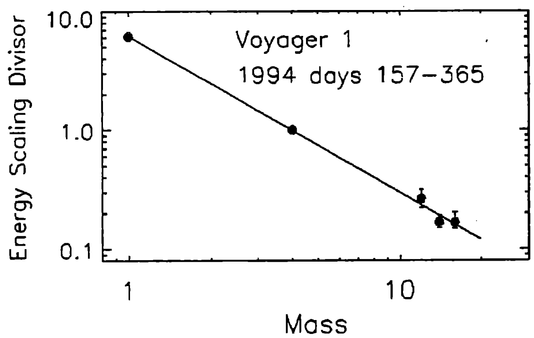

Figure 3. Energy scaling divisor vs. mass for ACR hydrogen, helium, carbon, nitrogen, and oxygen. This is the required energy scaling to fit the spectra of the other ACR components to helium (which is defined as 1.0). The line shows the least-squares power-law fit though the points.

4 Conclusion

The lower peak energy and increased flux at Voyager 1 in 1994 has resulted in a proton spectrum that shows a much more distinct signature of ACR hydrogen than was the case in 1987. However, combining the H/He ratio observed in 1994 with the clearly resolved ACR He spectrum in 1987 indicates that, in 1987, there should have been an ACR H flux comparable to that reported by [1].

Acknowledgements

We gratefully acknowledge the support of E.R. Christian by the NASA ACE Explorer Project, and the other authors by NASA contract NAS7-918 and grant NAGW-1919.

References

[1] E.R. Christian, A.C. Cummings, & E.C. Stone, Ap. J. Letters 334 (1988) L77
[2] J.P.L. Reinecke & H. Moraal, Ap. J. 392 (1992) 272
[3] L.A. Fisk, B. Kozlovsky, & R. Ramaty, Ap. J. Letters 190 (1974) L35
[4] M.E. Pesses, J.R. Jokipii, D. Eichler, Ap. J. Letters 246 (1981) L85
[5] L.A. Fisk, in *The Sun and the Heliosphere in 3 Dimensions*, ed. R.G. Marsden (Dordrecht: Reidel) (1986) 401
[6] G. Gloeckler et al., Science 261 (1993) 70
[7] E.R. Christian, A.C. Cummings, & E.C. Stone, Proc. 21st ICRC (Adelaide) 6 (1990) 186
[8] P. Bertin et al., JGR 98 (1993) 15193
[9] F.B. McDonald, private communication
[10] T.A. Rygg & J.A. Earl, JGR 76 (1967) 7445
[11] J.J. Quenby, J.A. Lockwood, & W.R. Webber, Ap. J. 365 (1990) 365
[12] W.R. Webber & M.S. Potgieter, ApJ 344 (1989) 779
[13] E.R. Christian, Evidence for Anomalous Cosmic Ray Hydrogen, PhD dissertation, Caltech (1989)
[14] E.R. Christian, A.C. Cummings, & E.C. Stone, ~~accepted in~~ Ap. J. Letters (1995) , 446, L
[15] A.C. Cummings, E.C. Stone, & W.R. Webber, Ap. J. Letters, 287 (1984) L99
[16] A.C. Cummings, & E.C. Stone, these proceedings
[17] A.C. Cummings, & E.C. Stone, Proc. 21st ICRC (Adelaide) 6 (1990) 202